The chemical enrichment of the ICM with BeppoSAX

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Abstract. We review observations on the chemical enrichment of the intracluster medium (ICM) performed using BeppoSAX MECS data. The picture emerging is that non-cooling flow clusters have flat metallicity profiles, whereas a strong enhancement in the abundance is found in the central regions of the cooling flow clusters. All the non-cooling flow clusters present evidence of recent merger activity suggesting that the merger events redistributes efficiently the metal content of the ICM. The observed abundance excess in the central regions of cooling flow clusters is probably due to metals ejected from the cD galaxy located in the cluster core. Cooling flow cluster have also enhanced Nickel abundances in their cores with respect to the non cooling flow clusters.

1. Introduction

The X-ray emission in clusters of galaxies originates from the hot gas permeating the cluster potential well. The continuum emission is dominated by thermal bremsstrahlung, which is proportional to the square of the gas density times a function of the gas temperature (i.e. the cooling function). From the shape and the normalization of the spectrum we derive the gas temperature and density. At the high temperatures measured in clusters the ICM is highly ionized (H and He are completely ionized). A measure of the equivalent width of a spectral line is a direct measure of the relative abundance of a given element. This comes from the fact that both the continuum and line emissions are two-body processes with the continuum emissivity proportional to the electron density times the proton density, and the line emissivity proportional to the electron density times the density of a given element. From the definition of equivalent width it is easily derived that this quantity is proportional to the ratio between the ion and proton densities.

In the 2-10 keV band Iron is the most easily measurable element in the X-ray spectrum. This is true for several reasons: the atomic physics of K-shell lines is well known; Fe is an abundant element in nature; the Fe-Kα line is well isolated in the spectrum and it is located in a region of the spectrum where the spectral resolution of the X-ray detectors is usually good. Other elements

measurable in the X-rays are K-shell lines of C, N, O, Ne, Mg, Si, S, Ar, Ca and Ni, and L-shell lines of Fe and Ni.

It is well known that the global Fe abundance in clusters is about a third of the solar value. The evolution of metal abundances of the ICM in clusters has been investigated by various authors and a common result is the lack of evolution within redshift about 0.3-0.4 (e.g. Allen & Fabian 1998). This is also confirmed by BeppoSAX measures on distant clusters (Della Ceca et al. 2000; Ettori, Allen & Fabian 2001).

While the origin of the metals observed in the ICM is clear (SNs make metals), less clear is the transfer mechanism of these metals from stars to the ICM. The main mechanisms that have been proposed for the metal enrichment in clusters are: enrichment of gas during the formation of the proto-cluster (e.g. Gnedin 1998, Kauffmann & Charlot 1998) ; ram pressure stripping of metal enriched gas from cluster galaxies (e.g. Gunn & Gott 1972, Toniazzo & Schindler 2001) ; stellar winds AGN- or SN-induced in Early-type galaxies (e.g. Matteucci & Vettolani 1988, Renzini 1997). As we shall see below clues to metal enrichment mechanisms can be derived from spatially resolved analysis of metal abundances.

An interesting result is that found by Allen & Fabian (1998) for a sample of cooling flow (CF) and non-cooling-flow (non-CF) clusters, where these authors found that CF clusters have global metallicities about 1.8 times higher that that of non-CF clusters. This difference could be explained by assuming that CF clusters have abundances excess in their cores. Understanding if the metal production in the ICM is segregated or if it is constant with the cluster radius is important because it leads to a more precise estimate of the metal amount in the ICM (e.g. the total iron mass) and gives clues to the transport mechanism(s) from galaxies to the ICM. Moreover, the comparison between the spatial distribution of metals and the optical light gives information on the galaxies which have contributed to the enrichment of the ICM.

2. Spatially resolved abundance measures in clusters observed with ASCA and BeppoSAX

ASCA and BeppoSAX have been decisive missions to explore spatially resolved abundance measurements in clusters. Various works have identified abundance gradients in a few cooling flow clusters, e.g. Ikebe et al. (1997) on Hydra A, Molendi et al. (1998) on Perseus cluster, Dupke and White (2000) on A496.

Metal abundance derived from ASCA data for samples of rich clusters are reported in Kikuchi et al. (1999), White (2000), Fukazawa et al. (1998), Fukazawa et al. (2000), Dupke and White (2000), Finoguenov, David and Ponman (2000). A general result from these works is the evidence of abundance gradients in several clusters, with an indication that abundance gradients are common in CF clusters, however the shape of these gradients is poorly determined. In fact the quality of the ASCA data does not allow a detailed investigation of the abundance gradients. A typical example is the case of A496 where abundance profile has been derived from ASCA data by three different working groups. In the first case Dupke & White (2000) derived an abundance gradient (see Figure 1 top panel) dividing the cluster emission into two bins only, one from 0 to 2
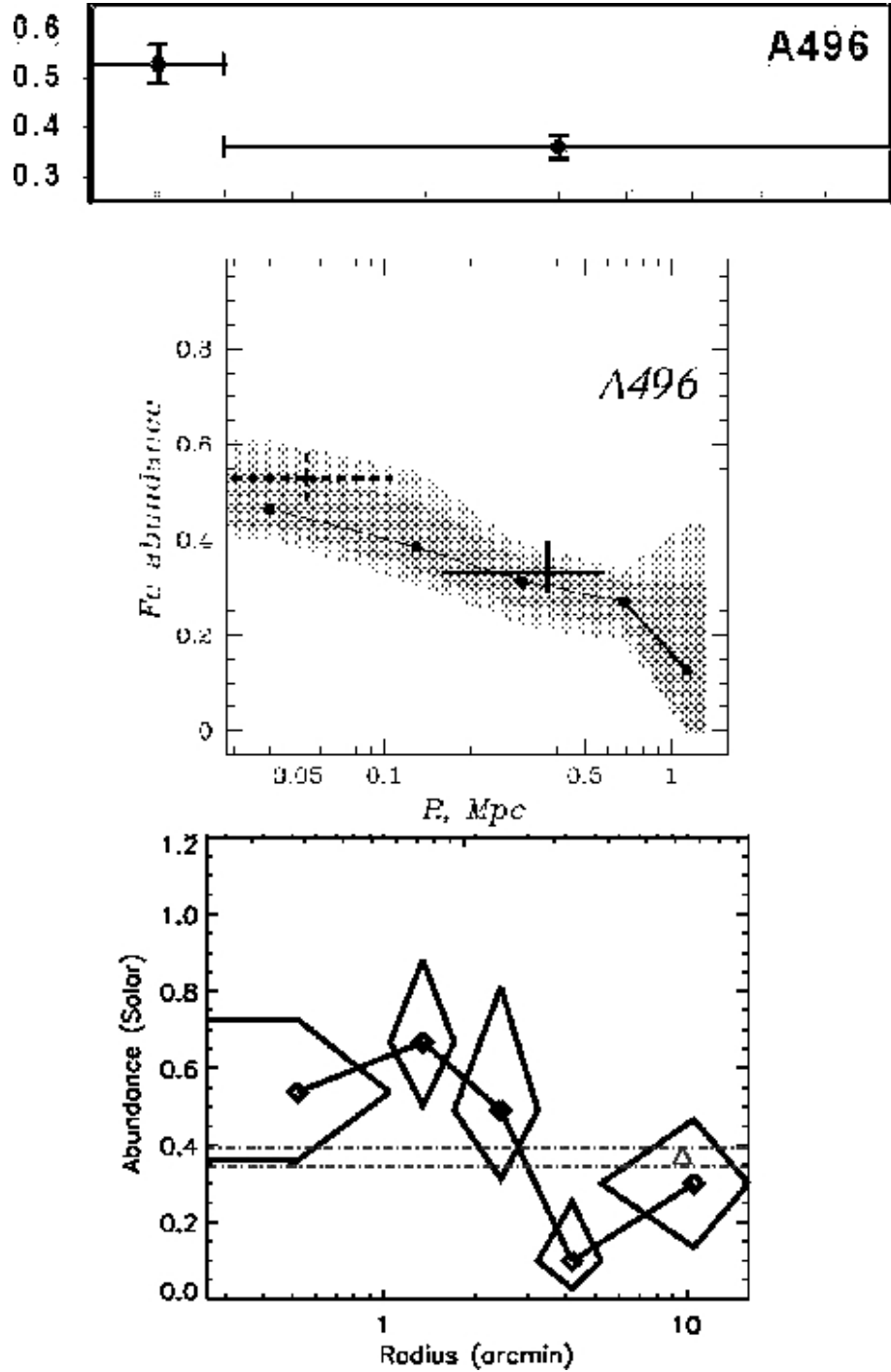
Figure 1.   Metallicity profile as a function of the radius in arcmin for cluster Abell 496 as observed with ASCA GIS. Top: Dupke & White (2000), the first bin ranges from 0 to 2 arcmin, the second bin from 2 to 12 arcmin. Middle: Finoguenov et al. (2000). Bottom: White (2000).
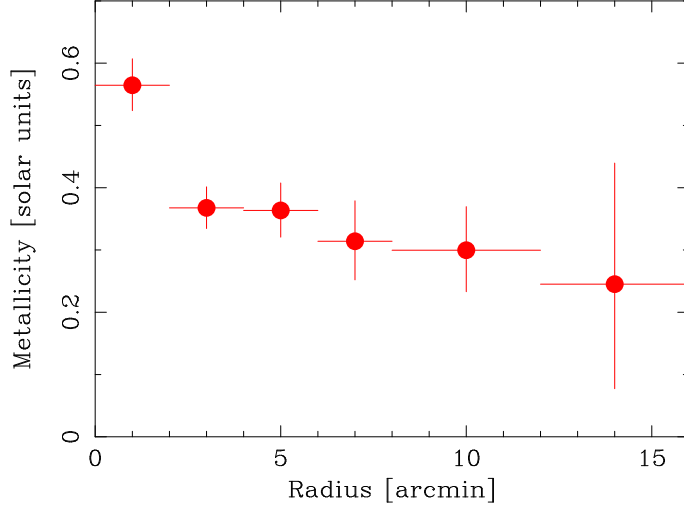
Figure 2.   Metallicity profile as a function of the radius in arcmin for cluster Abell 496 as observed with BeppoSAX MECS.

arcmin and the second one from 2 to 12 arcmin. In the second case Finoguenov et al. (2000) by increasing the number of bins (at the price of increasing the errors in the abundance measurements) up to four within 13 arcmin (Figure 1 middle panel) find evidences of for a smoothly declining gradient. In the last case, similarly to Finoguenov et al, White (2000) increased the numbers of bins up to 5 within 12 arcmin finding again an evidence for a smoothly declining gradient with large errors (see Figure 1 bottom panel). A comparison of all these three cases shows a poor determination of the real shape of the abundance gradient in A496. In Figure 2 we show the abundance profile as observed with BeppoSAX, the data are able to constrain the shape of the gradient revealing that the abundance excess is concentrated in the cluster core.

The difference between the ASCA and BeppoSAX metallicity profiles is due to the differences in the PSFs. The ASCA PSF is broad (HPR $\sim$ 2 arcmin), strongly energy dependent and non-radially symmetric, therefore the analysis of extended sources required complicated correction procedures (e.g. Markevitch et al. 1998, White & Buote 2000). On the other hand, BeppoSAX PSF is sharper (HPR $\sim$ 1 arcmin), is almost energy independent (D'Acri et al. 1997) and radially symmetric, therefore the analysis of extended sources is relatively straightforward (e.g. De Grandi & Molendi 2001). Moreover BeppoSAX exposure times are typically about three times larger than ASCA exposure times. From all these considerations it follows that BeppoSAX MECS data are better suited than ASCA to investigate abundance profiles for galaxy clusters.

Up to date there are two works based on BeppoSAX MECS samples which are systematically searching for abundance gradients in clusters. The first is an analysis of 12 clusters performed by Irwin & Bregman (2001). This analysis is limited to the 9 innermost arcmin of the cluster emission (i.e. radii $\lesssim$ 20% of the virial radius) and do not explore systematically the difference between CF
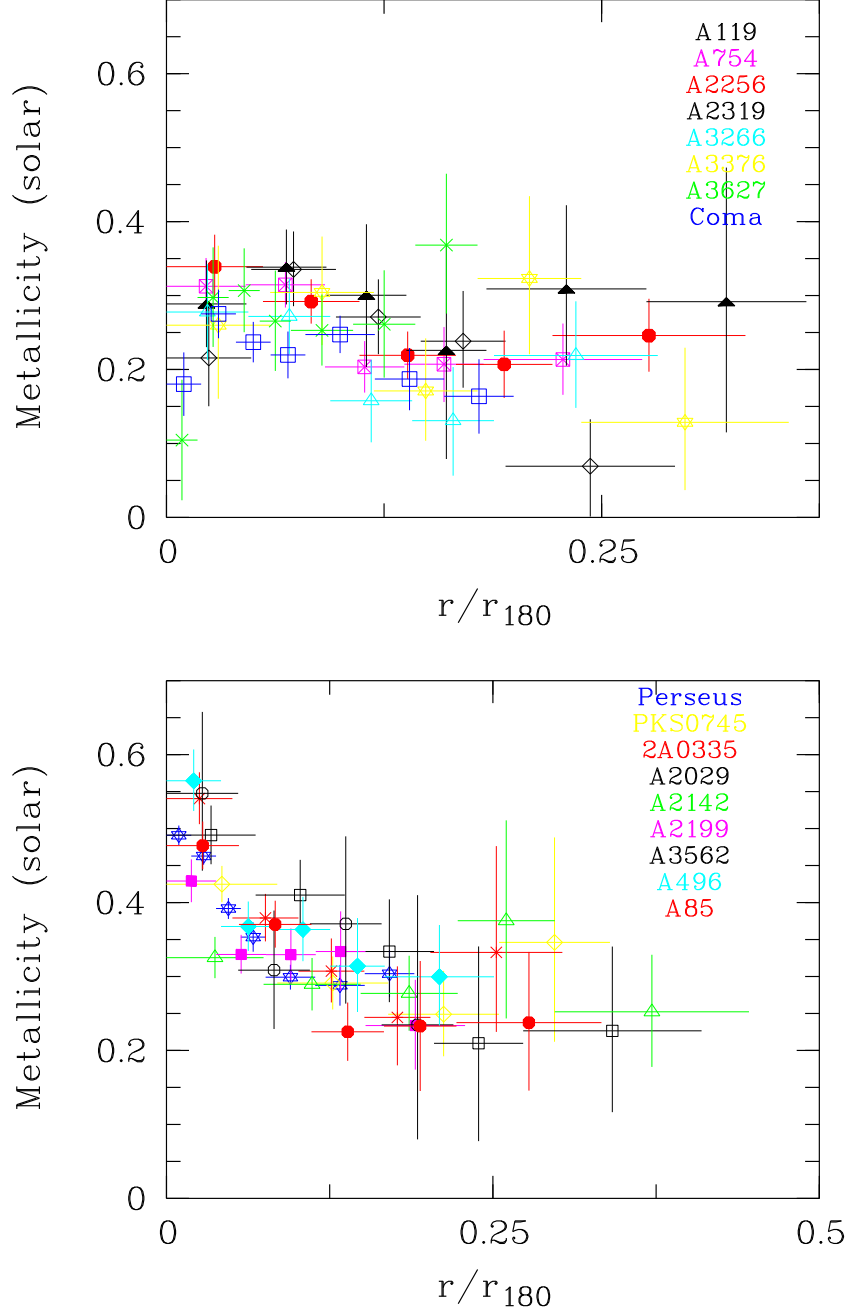
Figure 3.   Metallicity profiles (projected) for the non-CF (top) and CF (bottom) clusters, plotted against radii in units of r_{180}.
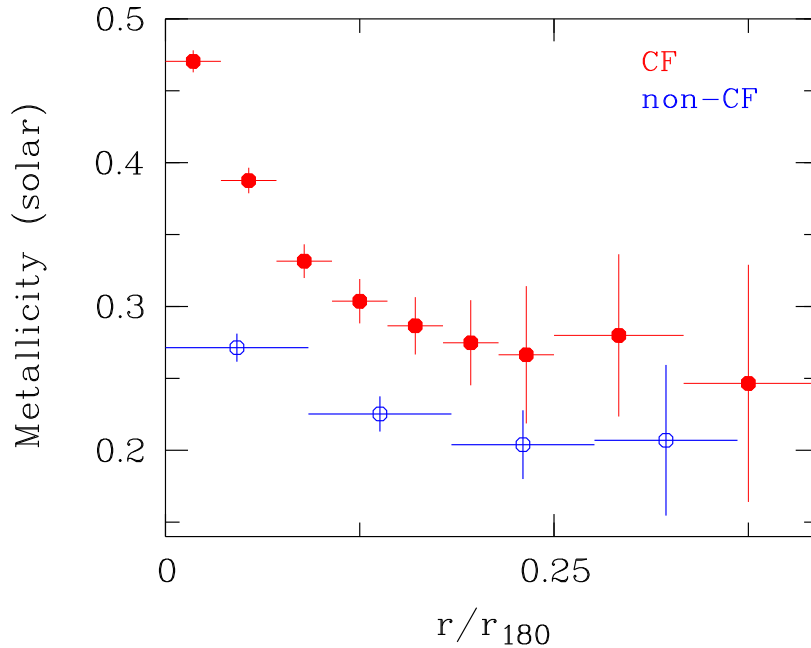
Figure 4.   Mean metallicity profiles for the CF (filled circles) and non-CF clusters (open circles), plotted against radii in units of r_{180}.

and non-CF clusters. Irwin & Bregman (2001) find a general evidence for a negative abundance gradient in most of the clusters.

The other work is that of De Grandi & Molendi (2001) on a sample of 17 clusters analyzed considering the whole field of view of the MECS (which corresponds to radii $\lesssim 50\%$ of the virial radius). The projected abundance profiles of the non-CF systems (Figure 3 top panel), are consistent with being constant with the radius. On the contrary the metallicity profiles of the CF clusters (Figure 3 bottom panel) is completely different showing a clear evidence of an abundance gradient declining with the radius in most of the systems.

In Figure 4 we compare the mean error-weighted abundance profile for CF and non-CF clusters. The metal abundances of the CF clusters are larger than 0.4 of the solar value in the central regions and decrease rapidly to values similar to those of the non-CF clusters at radii $\gtrsim 0.25$ r_{180}. The profile for non-CF clusters is much flatter, a fit with a constant to all non-CF abundance measurements is statistically acceptable. However, a small gradient is present in the data (significant at more than 99.5% level on the basis of an F-test). The comparison of the abundance profile for CF and non-CF clusters supports the scenario where major merger events disrupt the central regions of clusters thereby re-mixing the gas within these regions and therefore destroying pre-existing abundance gradients. The modest gradient observed in non-CF clusters is quite likely the relic of a much stronger gradient which has not been completely wiped out by merger events.

2.1. Implication for the enrichment mechanism of the ICM in CF cluster cores

If each merger events redistributes efficiently the metals within the ICM then the metal excess we see in the core of CF clusters should be directly related to the enrichment processes which have occurred in the cluster core since the last major merger. Thus, just as the global metallicity of clusters is an indicator of the global star formation history within the whole cluster, the abundance excess we see in the core of CF clusters is an indicator of the star formation history in the core of the cluster since the last major merger. In the light of the above statement, we have tried to test whether the metal abundance excess we see is due to metals expelled from early type galaxies located in the core of the cluster. More specifically we have computed the metal abundance excess profile expected when the metal excess distribution traces the light distribution of early type galaxies, included the cD galaxy (details are given in De Grandi & Molendi 2001). We have performed this computation for the 4 cooling flow objects where the metal abundance profile is best measured and optical data is available, namely: A85, A496, A2029 and Perseus (see Figure 5).

For A496 and A2029 the predicted projected metal abundance excess can be reconciled with the observed one, while for A85 the predicted projected metal abundance excess appears to be slightly more centrally concentrated than the observed one. The more interesting case is that of Perseus cluster, where the two profiles are substantially different.

We find that the abundance excess in the expected profiles is completely due to the cD galaxy. Fukazawa et al. (2000) computed that the amount of metal excess at the cluster center can be provided by the cD alone. Therefore we conclude that we are probably just observing the accumulation of metal ejection from the cD galaxy into the ICM, and suggest that a possible way of reconciling the observed and predicted abundance excess profile of Perseus is to assume that metals ejected from the central cD have drifted away by about 50 kpc.

3. BeppoSAX Nickel measurements

For an updated sample of 22 clusters (11 with CF and 10 without CF) we have measured Nickel abundances in the innermost regions of the clusters, i.e. for radii smaller than 200-400 kpc. The results are reported in Figure 6. This figure shows the Fe segregation between CF and non-CF clusters already discussed in the previous sections, as well as a difference for the Ni abundances.

The mean Fe abundance values for CF and non-CF clusters are, in solar units, 0.45±0.01 and 0.30±0.01, whereas the mean Ni abundances are 1.10±0.12 and 0.16 ± 0.17, respectively. We find a $\sim 5\sigma$ evidence for a Ni excess in the central regions of the CF clusters with respect to the central regions of non-CF clusters. This Nickel excess is probably associated to the cD galaxy as the Iron excess, indeed both elements are mostly produced by SN type Ia which are dominating the enrichment of the cluster central regions. The Nickel-to-Iron abundance ratio produced by the cD galaxy, defined as $[Ni/Fe]_{cD} = ([Ni]_{CF} - [Ni]_{non-CF})/([Fe]_{CF} - [Fe]_{non-CF})$, is 6.3 ± 1.4, normalized to the solar ratio.
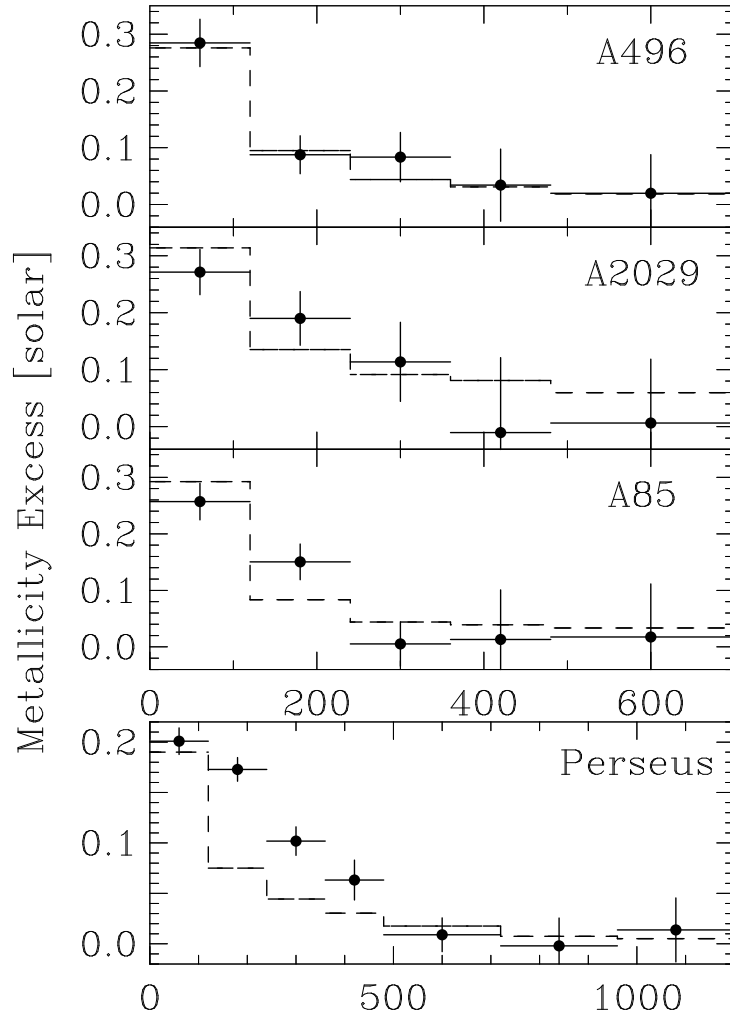
Figure 5.   Predicted (dashed lines) versus measured (solid circles) metallicity excess profiles as a function of radius for the cooling flow clusters A496, A2029, A85 and Perseus.
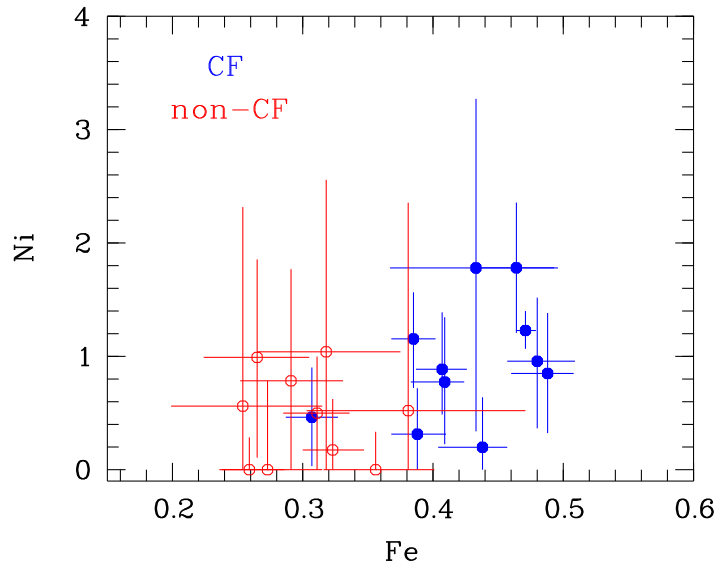
Figure 6.   Nickel vs. Iron abundances for non-CF (open circles) and CF (filled circles) clusters.

4.   References

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